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Motorization of China implies changes in Pacific air chemistry and primary production

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Abstract. The People's Republic of China, the world's most populous nation, is considering extensive development of its automotive transportation infrastructure. Upper limits to the associated pollution increases can be defined through scenarios with Western style vehicles and vehicle-to-person ratios. Here we construct estimates of fundamental changes to chemistry of the Pacific ocean/atmosphere system through simple budgeting procedures. Regional increases in tropospheric ozone could reach tens of parts per billion. Observations/experiments suggest that enhanced nitrogen oxides will react with sea salt aerosols to yield chlorine atoms in the marine boundary layer. Nitrate deposition onto the open sea surface would support several percent of exported North Pacific carbon production. Transport of biologically active iron to surface waters may follow from increases in mineral dust and acid sulfate aerosols. Altered plankton ecodynamics will feed back into climate processes through sea to air flux of reduced sulfur gases and through carbon dioxide drawdown.

Introduction

The economy of mainland China (the People's Republic or P.R.C.) is growing rapidly and a modernized transportation system is in the offing. Planning documents indicate that the Chinese government is preparing to expand its highway network to accomodate a vehicle fleet patterned after U.S., European and Japanese models (World Bank and Chinese Ministry of Communications, 1994). The popular press echoes government policy statements to this effect (Tyler, 1994; Barnathon et al., 1996; Engardio and Roberts, 1996). Prospects are for hundreds of millions of new autos in east Asia in the next century (World Bank and Chinese Ministry of Communications, 1994; Brown, 1995). By analogy with dispersal of North American air pollution to the Atlantic, major influences on the chemistry of the Pacific Rim are anticipated. Ozone, oxidant, nitrate and aerosol fields may be altered in the atmosphere (Keene et al., 1990; Galloway et al., 1992; Parrish et al., 1993; Galloway, 1996). Macro- and micronutrient cycles may be affected within the oceanic mixed layer (Duce, 1986; Owens et al., 1992). Global carbon dioxide emissions will rise (Marland and Rotty, 1984; Cutter, 1992).

The market for automobiles in the P.R.C. is potentially larger than in the U.S. and Europe combined (Zhihao, 1990; Sinton et al., 1992; Sathaye et al., 1994). It will be debatable whether Chinese vehicle/person ratios can actually reach Western levels, and even whether new Asian autos would be gasoline powered (Cutter, 1992; Brown, 1995). The dialog is likely to be a prominent feature of studies of Pacific air chemistry. However, useful guidance to possible pollution phenomena can be generated by extrapolation from Western situations (e.g. NRC, 1992; Michaels et al., 1993). We have recently modeled the increases in tropospheric ozone which could result from a large Chinese fleet implementation (Elliott et al., 1997). Here we condense results from the ozone simulations and couple them with an examination of overall Pacific chemistry issues. The regional tropospheric oxidizing capacity is subject to alteration (Thompson, 1992; Finlayson-Pitts, 1993). Nutrient cycle effects are likely within the sea (Michaels et al. 1993; Martin et al., 1994). Our arguments can be viewed as a surface transportation subset of predictions for effects of Asian energy use (Galloway et al., 1996). Since the future Chinese auto remains for the moment a speculation, our calculations are restricted to the budgetary level.

We begin by establishing baseline inputs. The new Chinese fleet could exceed that in the U.S by a factor of two or more in size (Cutter, 1992). Performance will be difficult to predict without engineering and maintenance information (Zhang et al., 1995). Upper limit emissions are thus set an order of magnitude above those from eastern North America. Major chemical pollutant increases are next outlined: ozone/oxidants, nitrate/iron as marine nutrients, and others. Feedbacks into the climate system are enumerated. Loops exist from nutrients through bioproduction to climate controlling gases (Kieber et al., 1995). The circuits are poorly understood (Zhuang et al., 1992) but new Chinese autos could amplify them. A closing discussion emphasizes uncertainties such as fuel reserves and vehicle production capacity.

The Emerging Fleet and Emissions

The eastern United States supports synoptic scale ozone pollution, and with continental outflow the oxidants reach the open Atlantic (Parrish et al., 1993). About 75 million gasoline powered automobiles/trucks are to be found in eastern North America (MVMA, 1990). The ratio of vehicles to persons is 0.5 (UN, 1992). Population in the People's Republic of China has surpassed 1 billion (UN, 1990; WRI, 1992). At per person ratios from the Western world, the Chinese comprise a market for over half a billion automobiles (Sinton et al., 1992; Sathaye et al., 1994). Such maxima may not be economically sustainable, but vehicle densities several times those in the U.S. east seem plausible. The vehicle/person quotient in the compact island nation of Japan is now 0.3, and in Singapore is almost identical with that of Manhattan island (WRI, 1992; UN, 1992). The current Chinese fleet is negligibly small. Even early in the next century, however, it is expected to grow by 2-4 million units/year (Brown, 1995).

It is difficult to predict the quality of new Asian autos. Several established carmakers are positioning to fill the niche (McCosh, 1996). The Chinese may retool their bicycle/truck industries to meet demand (Brown, 1995). Centralized economies in eastern Europe produced polluting vehicles (Grosse, 1995). On the other hand, the Chinese have a reputation for quality high technology manufacturing

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(Sinton et al., 1992; Barnathon et al., 1996). Maintenance is an oft overlooked factor determining auto emissions (Zhang et al., 1995). Authoritarian regimes have a good record on some types of emissions control (Brown, 1995).

Coming auto emissions from the Chinese mainland are obviously highly uncertain at present. As a starting point we assume inputs of VOC and NOx could reach ten times current levels for the eastern U.S. Note that uncertainties in both total vehicle number and in individual unit emissions are enfolded. Despite advances in hydroelectric power and oil exploration, the Chinese economy is likely to remain coal based (Smil, 1988; Sinton et al., 1992). A growing automobile industry will thus increase sulfur oxide emissions as well.

Ozone and Oxidants

Since the pristine Pacific is a major concern, our focus in constructing oxidant budgets will be on springtime meteorology; westerly winds dominate (Merrill et al., 1985). Ozone production can be estimated via oxidation yields from well studied areas (Jacob et al., 1993; Chin et al., 1994). A populated corridor 1000 km west to east may be defined for the eastern P.R.C., with the winds passing over the surface at 5 m s^{-1} (Kotamarthi and Carmichael, 1990). The accumulation time is then 2 days. The eastern U.S. produces about 2 x 10^{11} NOx molecules cm^{-2} s^{-1} (Hameed and Dignon, 1992), of which half is attributable to cars/trucks (NRC, 1992). VOC to NOx ratios are poorly constrained for China but have been estimated at 5 (C to N atoms; Kotamarthi and Carmichael, 1990), toward the low end of the urban range (NRC, 1992). Several groups derive ozone yields of 1.5 per carbon for generalized continental organics (Jacob et al., 1989; Elliott et al., 1996). With emissions increased an order of magnitude, air traveling from central China to the Pacific acquires 10^{18} atoms cm^{-2} of organic carbon and generates 1.5 x 10^{18} molecules cm^{-2} of ozone.

Background tropospheric column ozone is on the order of 40 Dobson units at Asian midlatitudes (Sunwoo and Carmichael, 1992), or, 8 x 10^{17} molecules cm^{-2}. The emerging Chinese vehicle fleet could increase the column severalfold. Precursors concentrate in the lower half of the troposphere near Japan (Kotamarthi and Carmichael, 1990). Table 1 consolidates the results. Similar values are obtained from yields relative to nitrogen oxides (Liu et al., 1987; Jacob et al., 1993; Chin et al., 1994). A two dimensional full photochemical model has been constructed to investigate nonlinearities at the high emissions (Elliott et al., 1997). Ozone production is simulated in spring westerlies passing over China and on to the Pacific. For ten times the U.S. vehicular source the average below 5 km is 140 ppb over Japan. The model follows Kotamarthi and Carmichael (1990), but employs a family integrator (Elliott et al., 1996). Regional NMHC are represented by acetylene, ethane, ethylene, propane, propylene and isoprene decay sequences. Three dimensional simulations will be needed for corroboration, but our calculations definitely point to large increases.

Tropospheric ozone exerts greenhouse control over terrestrial climate. Furthermore, concentrations of other major oxidants will be affected in conjunction (e.g. OH, H_2O_2; Thompson, 1992). Chlorine atom is an initiator of organic oxidations in the marine boundary layer (Keene et al., 1990; Singh et al., 1996). Sources remain poorly understood, but involve reaction of nitrogen oxides with sea salt particles and so may have proportionality with NOx fields (Finlayson-Pitts, 1993). As critical as these factors are, downwind air pollution may be the chief political consequence. Oxidants generated in the U.S./Canada can cross the Atlantic (Hough and Derwent, 1990). The Pacific basin is larger, but transit times of under a week are known. The ozone signature from a Chinese vehicle fleet may reach North America. Japanese concerns, of course, are more immediate (Sunwoo et al., 1994).

Table 1. Ozone Densities in Columns Spanning the Entire Troposphere, and Half the Total Mass (<5 km). Units are Molecules per Square Centimeter.

	Current	Current+(U.S.x10)
Total	$8x10^{17}$ (40 ppb)	$2.3x10^{18}$ (130 ppb)
<5 km	$4x10^{17}$ (40 ppb)	$1.9x10^{18}$ (220 ppb)

Table 2. A Comparison of Nitrogen Exported from Euphotic Zones in Major Areas of the Global Ocean with Present Day Inputs of Oxidized Species from the Atmosphere. Units are Tmoles N Per Year.

	World	NA	SA	NP	SP
N export	120	15	15	25	30
N deposition	1	0.3	0.04	0.3	0.14
%	0.8	2.0	0.3	1.2	0.5

Oceanic Nutrients

A first step in examining global cycles for marine nutrient elements is to subdivide at the basin level (Duce, 1986; Duce et al., 1991). We begin our analysis of effects on Pacific biota using this approach. To estimate anthropogenic impact on ocean biological production, annual average NOx/nitrate deposited from the atmosphere can be compared with the nitrogen required to support downward carbon export from the euphotic zone (Galloway et al., 1995). The yearly world total for organic carbon removed to the deep sea is around 10 Gt (Siegenthaler and Sarmiento, 1993), or one fifth of world marine primary production. At the Redfield ratio of 7 C/N (Takahashi et al., 1985), this translates to 120 teramoles of nitrogen per year (Tmole N). As a conceptual expedient we here apportion nitrogen sinkage to the various basins purely according to their surface areas. Actual productivity data could be integrated to account for differences in margin recycling (Berger and Wefer, 1991) or deep nutrient concentrations (Duce, 1986). For our purposes the results are similar. Table 2 compares the partitioned export with atmospheric nitrogen oxide deposition rates from Duce et al. (1991). Current Northern Hemispheric pollution sources are readily apparent. The Chinese maximum postulated here amounts to spreading ten times the annual U.S. vehicular source to the Atlantic (ten times half of 0.2 to 0.3 Tmoles N) over somewhat less than twice the seawater surface area. The potential exists to raise the anthropogenic contribution to Pacific export production from the fractional percent to the several percent range.

The ozone budgeting performed here was specific to coastal and Western Pacific regions and to the spring. By contrast, our nutrient computations deal in time and space averaging. Two important reasons can be cited. 1.) Treating basin-wide nitrogen behavior permits circumvention of NOx-NOy transformation issues (Penner et al., 1991). The validity of the approach is implied in the Duce series (Duce, 1986; Duce et al., 1991). Since all nitrates are thought to be bioavailable, atmospheric nonlinearities are not a factor. 2.) Local nitrogen fluxes from the thermocline and deep sea are difficult to quantify. Wind driven exchange is a major source, but input is uncertain (McCarthy and Carpenter, 1983).

Michaels et al. (1993) point out that in the Sargasso Sea, atmospheric nitrogen deposition episodes lead to planktonic blooms observable by satellite ocean color instruments. The events correlate slow turnover rates in the upper meters of water and are significant a few percent of the time. Analogous but larger effects on Pacific biology would be expected if the P.R.C. motorizes. At some latitudes both export and primary production fall off more steeply moving away from Asia than do atmospheric nitrate concentrations (Berger and Wefer, 1991; Penner et al., 1991). The relative importance of aeolian N addition could be skewed toward the open sea. The local fate of nitrate deposited in sea water will depend on the availability of alternate nutrients such as phosphorus (Fanning, 1989). The ensuing nitrogen cycling should be modeled in high resolution OGCM codes.

Iron borne to the maritime regime in mineral dust functions as an oceanic micronutrient. The aeolian input rivals both riverine and deep sea fluxes to the euphotic zone (Duce, 1986). Variability in concentrations of the metal may have regulated CO2 uptake during glacial transitions (Martin, 1990). It is demonstrably a determinant of productivity in present day High Nutrient Low Chlorophyll waters (HNLC; Martin et al., 1994). Some HNLC areas are accessible to Asian transport. Mechanisms of iron extraction from solids remain controversial, but bioavailable (soluble) forms seem to result mainly from dissolution of oxides into acidic atmospheric waters, and from photoreduction of Fe(III) to Fe(II) during long range transit (Zhuang et al. 1992). Automobiles have been introduced into Asian cities faster than highway capacity could be created (Sathaye et al., 1994). There is the potential for a new Chinese fleet to suspend iron bearing particles. The latest studies of dust transport for Asia (Zhang et al., 1994) and for the globe (Tegen and Fung, 1995) cite agriculture and desertification as growing sources. No mention is made of motorization. However, the level of automotive activity being contemplated for mainland China is unprecedented. Furthermore, the P.R.C. currently possesses the smallest percentage of paved road of any major country (WRI, 1992; Brown, 1995). Since the Chinese economy is likely to remain coal based, a large automotive industry could add to sulfate release and aerosol acidity.

Numerous substances connect oceanic primary productivity with global climate. Nutrients support photosynthesis and the building of tissue. The biota emit dimethyl sulfide and organohalogens directly at rates with complex ecodynamical dependencies (Keller et al., 1989; Lobert et al., 1995). Decomposition yields dissolved organic matter, which photolyzes to produce low molecular weight hydrocarbons (Ratte et al., 1993), and carbonyl sulfide (Weiss et al., 1995). The location of DMS enhancements may be crucial since the molecule oxidizes in the marine atmosphere to produce condensation nuclei which in turn interact with cloud fields. The P.R.C. automotive buildup underscores the need for ocean atmosphere system modeling.

Miscellaneous

Aside from water vapor, carbon dioxide is the major climate altering material in the atmosphere. It constitutes the vast majority of vehicular C emissions by mass (Marland and Rotty, 1984). About one quarter of fossil fuel related CO2 emissions derive from the automotive sector (Marland and Rotty, 1984; Cutter, 1992). The global fleet of cars and trucks stands at about 400 million (MVMA, 1990). In our maximum scenarios the emerging Chinese contingent adds as much as 30 percent to the overall fossil CO2 source. Fertilization of the Pacific would lead to carbon drawdown, but the compensation is small. An increase of 5 percent in export of carbon to the deep North Pacific, or less than 1 percent globally, translates to less than 0.1 Gt per year. Fossil fuel inputs of CO2 to the atmosphere are today about 6 Gt C annually (Cline, 1992; Siegenthaler and Sarmiento, 1993). Mainland China could thus provide an extra 2 Gt per year of carbon to the climate system. The major offset may in fact be through the dimethyl sulfide feedback. In addition to the pollutants already detailed, automobiles will generate soot and organic aerosols, with uncertain effects on radiative forcing (Penner et al., 1994; Parungo et al., 1994).

Summary and Discussion

The People's Republic of China is considering options for providing individual motor vehicle transportation to its immense population (World Bank and Chinese Ministry of Communications, 1994). If a forthcoming Chinese automotive industry were patterned after that in the West, airborne pollutants would include massive quantities of ozone precursors, dust, acids and carbon dioxide (Marland and Rotty, 1984; Duce et al., 1991; Parrish et al., 1993). We estimate here that large oxidant concentration and nitrate deposition increases are entailed over the North Pacific. The nitrate fluxes into the ocean are sufficient to enhance biological export production (Berger and Wefer, 1991). Feedback loops from the marine biota into climate pass through dimethyl sulfide and carbonyl sulfide, among other species. Sulfate and mineral dust may interact to solubilize and transport iron to the open sea, where it can be a limiting micronutrient (Zhuang et al., 1992). Carbonaceous aerosols will be created as well.

The arguments presented are uncertain at many levels. The Chinese fleet under discussion is roughly the size of the current world total (MVMA, 1990). Unless the usual decadal vehicle lifetime could be raised (Cutter, 1992), sustaining the hundreds of millions of new autos/trucks would require a duplication of the global production capacity. It is clearly debatable whether such an enormous buildup can occur. It is valid to question the ability of the P.R.C. to fuel a national fleet. Chinese oil reserves remain largely a mystery to the West; in a recent analysis British Petroleum states only that they exceed those of the U.S. (McCreary et al., 1996). The perspective of the global energy marketplace is a useful one. Recoverable crude oil is sufficient to drive the world vehicle total even if a large Chinese fleet comes on line (Sundquist, 1990; Cline, 1992). Oil shale and coal extend any thresholds. Fuels alternative to gasoline are of course a possibility, but might actually increase nitrogen oxide emissions.

The effects outlined here for the marine environment can all be observed in microcosm in the North Atlantic, driven by the human population of eastern North America (Owens et al., 1992; Parrish et al., 1993). The market for U.S. automobiles, however, is near saturation. Many authors remark on the difficulty human cultures experience in avoiding or handling the transition to an auto based economy. The comments come from a variety of viewpoints (Williams, 1991; Sathaye et al., 1994; Smith et al., 1994; Brown, 1995; Goldemberg, 1995). While even the feeding of a nation so large as the P.R.C. should be a major issue in the next millennium (Chameides et al., 1994; Brown, 1995), so too will be its grappling with the conundrums of modern transportion.

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References

Barnathon, J. et al., Rethinking China, Business Week, March 4, 57-58, 1996.

Berger, W.H. and G. Wefer, Productivity of the glacial ocean; the iron hypothesis, Limnol. Oceanogr., 36, 1899-1918.

Brown, L. R., State of the World, Norton, New York, 1995.

Chameides, W. et al., Growth of continental scale metro-agro-plexes, regional ozone pollution and world food production, Science, 264, 74-77, 1994.

Chin, M. et al., Relationship of ozone and CO over North America, J. Geophys. Res., 99, 14, 565,-14, 573, 1994.

Cline, W. R., The Economics of Global Warming, Institute for International Economics, Washington,D.C, 1992.

Cutter (Information), Steps To Reduce Greenhouse Gases, Cutter Information Corp., Arlington, Mass., 1992.

Duce, R.A., The impact of atmospheric nitrogen, phosphorus and iron species on marine biological productivity, in The Role of Air Sea Exchange in Geochemical Cycling, edited by P. Buat Menard, pp. 497-529, D. Reidel, 1986.

Duce, R. A. et al., Atmospheric input of trace species to the ocean, Global Biogechemical Cycles, 5, 193-259, 1991.

Elliott, S. et al., A streamlined family photochemistry package reproduces nonlinearities in the global tropospheric ozone system, Computers and Chemistry, 20, 235-259, 1996.

Elliott, S. et al., Regional to global atmospheric effects of the emerging mainland Chinese transportation system, J. Atmos. Chem., in press, 1997.

Engardio, P. and D. Roberts, Global tremors from an unruly giant, Business Week, March 4, 59-64, 1996.

Fanning, K.A., Influence of atmospheric pollution on nutrient limitation in the ocean, Nature, 339, 460-463, 1989.

Finlayson-Pitts, B.J., Chlorine atoms as a tropospheric oxidant in the marine boundary layer, *Research of Chemical Intermediates*, **19**, 235-249, 1993.

Galloway, J.N., Anthropogenic mobilization of sulphur and nitrogen, *Annu. Rev. Energy Env.*, **21**, 261-292, 1996.

Galloway, J. N. et al., Sulfur and nitrogen in the North Atlantic Ocean's atmosphere, *Global Biogeochemical Cycles*, **6**, 77-100, 1992.

Galloway, J.N. et al., Nitrogen fixation: anthropogenic enhancement and the response, *Global Biogeochemical Cycles*, **9**, 235-252, 1995.

Galloway, J.N. et al., Nitrogen mobilization in the United States and the People's Republic of China, *Atmos. Environ.* **30**, 1551-1561, 1996.

Goldemberg, J., Energy needs in developing countries and sustainability, *Science*, **269**, 1058-1059, 1995.

Grosse, H. J., Abatement of air pollution in the GDR, *Pure and Applied Chemistry*, **67**, 1407 - 1486, 1995.

Hameed, S. and J. Dignon, Global emissions of nitrogen and sulfur oxides in fossil fuel combustion 1970-1986, *J. of the Air & Waste Manage. Assoc.*, **42**, 159-162, 1992.

Hough, A. M. and R.G. Derwent, Changes in global tropospheric ozone due to human activities, *Nature*, **344**, 645-647, 1990.

Jacob, D. J. et al., LIV method for simulating tropospheric ozone, *J. Geophys. Res.*, **94**, 8497-8510, 1989.

Jacob, D. J. et al., Factors regulating ozone over the U.S. and its export to the global atmosphere, *J. Geophys. Res.*, **98**, 14,817-14, 826, 1993.

Jenkins, W.J. and J.C. Goldman, Seasonal oxygen cycling and primary production in the Sargasso Sea, *J. Mar. Res.*, **43**, 465-491, 1985.

Keller, M.D. et al., Dimethyl sulfide production in marine phytoplankton, in *Biogenic Sulfur in the Environment*, edited by E.S. Saltzman, ACS, Washington D.C., 1989.

Keene, W.C. et al., The geochemical cycling of reactive chlorine through the marine troposphere, *Global Biogeochemical Cycles*, **4**, 407-430, 1990.

Kieber, D.J. et al., Impact of dimethyl sulfide photochemistry on sulfur cycling in the equatorial Pacific Ocean, *J. Geophys. Res.*, **101**, 3715-3722, 1996.

Kotamarthi, V. K. and G.R. Carmichael, The long range transport of pollutants in the Pacific Rim region, *Atmos. Environ.*, **24A**, 1521-1534, 1990.

Liu, S. C. et al., Ozone production in the rural troposphere and the implications for regional and global ozone distributions, *J. Geophys. Res.*, **92**, 4191-4207, 1987.

Lobert, J.M. et al., The ocean as a net sink for atmospheric methyl bromide, *Science*, **267**, 1002-1005, 1995.

Marland, G. and R.M. Rotty, Carbon dioxide emissions from fossil fuels, *Tellus*, **36B**, 232-240, 1984.

Martin, J.H., Glacial-interglacial CO2 change: the iron hypothesis, *Paleoceanography*, **5**, 1-13, 1990.

Martin, J.H. et al., Testing the iron hypothesis in ecosystems of the equatorial Pacific, Nature, 371, 123-129, 1994.

McCarthy, J.J. and E.J. Carpenter, Nitrogen cycling in the open ocean, in *Nitrogen in the Marine Environment*, edited by E.J. Carpenter and D.G. Capone, pp. 487-512, Academic Press, New York, 1983.

McCosh, D., A Car for China, *Pop. Sci.*, Aug., 56-59, 1996.

McCreary, E.I. et al., *China's Energy: Forecast to the Year 2015*, Report LA-UR-96-2972, Los Alamos 1996.

Merrill, J. T. et al., Modeling transport to the Marshall Islands, *J. Geophys. Res.*, **90**, 12,927-12,936, 1985.

Michaels, A.F. et al., Episodic inputs of atmospheric nitrogen to the Sargasso Sea: new production and plankton blooms, *Global Biogeochemical Cycles*, **7**, 339-352, 1993.

MVMA (Motor Vehicle Manufacturer's Association), *Facts and Figures*, MVA, Detroit, Michigan, 1990.

NRC (National Research Council), *Rethinking the Ozone Problem in Urban and Regional Pollution*, National Academy Press, Washington, D.C., 1992.

Owens, N.J.P. et al., Atmospheric nitrogen deposition to oligotrophic oceans, *Nature*, **357**, 397-399, 1992.

Parrish, D. D. et al., Export of North American ozone to the North Atlantic, *Science*, **259**, 1436-1439, 1993.

Parungo, F. et al., Transport of black carbon from China to the ocean, *Atmos. Environ.*, **28**, 3251-3260, 1994.

Penner, J. E. et al., Tropospheric nitrogen: a three-dimensional study of distributions and deposition, *J. Geophys. Res.*, **96**, 1587-1590, 1991.

Penner, J. E. et al., Quantifying and minimizing uncertainty of climate forcing by anthropogenic aerosols, *Bulletin of the American Meteorological Society*, 375-394, 1994.

Ratte, M. et al., Production of C2-C4 hydrocarbons in seawater: measurements and experiments, *Global Biogeochemical Cycles*, **7**, 369-378, 1993.

Sathaye, J. et al., Transportation, fuel use, and air quality in Asian cities, *Energy*, **19**, 573-686, 1994.

Siegenthaler, U. and J.L. Sarmiento, Atmospheric carbon dioxide and the ocean, *Nature*, **365**, 119-125, 1993.

Singh, H.B. et al., Low ozone in the marine boundary layer of the tropical Pacific: photochemical loss, chlorine atoms and entrainment, *J. Geophys. Res.*, **101**, 1907-1917, 1996.

Sinton, J. E., *China Energy Databook*, report LBL-32822.Rev.3, UC-350, Lawrence Berkeley, 1992.

Smil, V., *Energy in China's Modernization: Advances and Limitations*, M. E. Sharpe, London, 1988.

Smith, K. R. et al., Air pollution and the energy ladder in Asian cities, *Energy*, **19**, 587-600, 1994.

Sundquist, E., Long term aspects of atmospheric CO2, in *Sea Level Change*, edited by R. Revelle, pp. 193-207, National Academy Press, 1990.

Sunwoo, Y. and G. Carmichael, Tropospheric ozone in the western Pacific Rim, *Quadrennial Ozone*, 225-227, 1992.

Sunwoo, Y. et al., Characteristics of background surface ozone in Japan, *Atmos. Environ.*, **28**, 25-37, 1994.

Takahashi, T. et al., Redfield ratio from chemical data on isopycnals, *J. Geophys. Res.*, **90**, 6907-6924, 1985.

Tegen, I. and I. Fung, Contribution to the atmospheric mineral aerosol load from surface modification, *J. Geophys. Res.*, **100**, 18707-18726, 1995.

Thompson, A.M., The oxidizing capacity of the earth's atmosphere, *Science*, **256**, 1157-1165, 1992.

Tyler, P., China planning people's car to put masses behind the wheel, *New York Times*, September 22, 1994

UN (United Nations), *Demographic Yearbook, 1988*, Publishing Division, New York, 1990.

UN (United Nations), *Urban Air Pollution in Megacities of the World*, Blackwell, Oxford, 1992.

Weiss, P.S. et al., Open ocean source of OCS to the atmosphere, *J. Geophys. Res.*, **100**, 23083-23092, 1995.

Williams, H. *Autogeddon*, Arcade, New York, 1991.

World Bank and Chinese Ministry of Communications, *China: Highway development and management issues, options, and strategies*, report No. 13555-CHA, 1994.

WRI (World Resources Institute), *World Resources 1992 and 1993*, Oxford University Press, Oxford, 1992.

Zhang, Y. et al., Photochemical oxidant processes in the presence of dust: an evaluation of the impact on particulate nitrate and ozone, *J. Appl. Met.* **33**, 813-824, 1994.

Zhang, Y., Worldwide vehicle exhaust emissions by remote sensing, *Environ. Sci. and Tech.*, **29**, 2286-2296, 1995.

Zhihao, W., Bicycles in cities in China, in Developing World Transport, edited by M.J. Heraty, pp. 130-134, Grosvenor International, London, 1990.

Zhuang, G. et al., Link between iron and sulphur cycles suggested by detection of Fe(II) in marine aerosols, *Nature*, **355**, 537-539, 1992.

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